Developing a High-Fidelity Knowledge Base for Non-Destructive Testing and Composite Material Products: A Review

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Abstract

Coping with the growing global concern of climate change places an imperative on the transportation industry to react. Adopting composite materials can be considered a logical solution for light-weighting; they play a vital role due to their unique properties that can be tailored to requirements. For composite materials to succeed in replacing conventional materials, they must be designed to a lightweight criterion with safety margins essential to guarantee the safety of consumers. Non-destructive testing (NDT) is used to ensure safety and confirm that a component is fit for purpose. However, the National Composites Centre (NCC), Bristol, UK has identified gaps in understanding the state-of-the-art for NDT methods for composites inspection in industry. An opportunity exists to further NDT understanding by developing a detailed knowledge base mapping material, component and defect configuration to capabilities and limitations of detection methods. Tacit knowledge captured in a capability matrix provides NDT operators/engineers with explicit, validated applicability data to support method selection for application, ultimately acting as a decision tool when deployed in the NCC's upcoming Composites Integrity Verification Cell. The database can be used to augment engineering teams' operations and confidence through the design of efficient structures, capable of satisfying future sustainability goals.

(199 words)

1 Introduction

With the growing global opportunities for the application of composite materials in multiple sectors, the UK composite product market is expected to reach £12bn in 2030 (valued at £2.3bn in 2016). Growth is predicted in all sectors; in established areas such as Aerospace and Defence, in rapid growth areas such as Automotive and Renewables and into the newer areas of Oil & Gas, Rail and Construction [1].

The versatility of composites is attractive for many industrial purposes; stiffness, strength, toughness and corrosion resistance can be tailored to requirements [2]. Additionally, composite materials have exceptional stiffness-to-density ratios, and lighter materials drive weight-savings for lower operating costs. Composite materials constitute around 50% of the Boeing 787 aircraft (including structures such as fixed leading edge and trailing edge panels) and provide an average weight saving of 20% [3]. Improving efficiency through weight reduction is a logical method to meet a legislative target of CO_2 emissions in the automotive industry where car body-in-white weight becomes more important in the transition towards the electrification of vehicles [4].

In transportation industries, inspection can be the difference between life and death. Non-destructive testing (NDT) encompasses a range of techniques that can be used to probe safety-critical structures for defects that reduce structural performance of the component or could potentially cause catastrophic failure. It is necessary to ensure the component is fit for purpose and confirm safety of consumers.

It has been identified that gaps in understanding the current capabilities and limitations of NDT methods exist in industry, compromising the effectiveness of a method to detect anomalies in a structure. An improved comprehension of detection methods can lead to increased confidence in the assurance of safety therefore, to support this, the National Composites Centre (NCC), Bristol, UK has identified the need for establishing a composites material inspection database.

This paper discusses the development of a detailed knowledge base that focuses on gaps in understanding by mapping material, component and defect configurations to the capabilities and limitations of NDT methods. The review addresses ultrasonic, thermographic and shearographic technologies that are applicable to NCC projects.

2 Literature Review

2.1 Design Variability

Composites are particularly susceptible to the appearance of defects, defined here as an irregularity in a material or structure that causes it to depart from its specification as defined during the design process. These defects can occur in the design and manufacturing phases, and during the in-service life of the component [5]. Potter et al. have identified more than 130 defect types and more than 60 sources of variability and unreliability for autoclave and resin transfer moulding processes. It is difficult to state at what point exactly a feature/consequence of variability becomes a defect [6]. It can be considered that largest source of variability may be a lack of understanding of manufacturing, or the design practices used to arrive at the component design [5], leading to unwanted features that may have been overlooked [4].

2.2 Defect Characterisation

Non-designed features that can be introduced into composite structures due to design decisions and manufacturing actions include delamination/disbond defects, fibre misalignment and porosity (void content). Defect occurrence, size, and frequency depends on the component's design characteristics and its process cycle [7]. Since the properties of composites are strongly influenced by their constituent materials, their distribution, and the interaction among them [8], defects may lead to stress concentrations with the potential to knock down mechanical performance. Therefore, it is important to test the structural integrity of the a composite in order to avoid the possibility of catastrophic failure [9].

There are performance requirements which a part must meet for it to conform to its design specification. The acceptance criteria, or acceptable limits, for manufacturing and in-service defects specific to the component application, are therefore defined such that 'allowable' defect type/size/location characteristics are used as a threshold to account for inherent variability. The guidelines of the acceptance criteria should be unambiguous, complete and testable [7], [10]. Identification of the location of where defects are likely to occur, and description of their morphology is essential prior to attempting to assess whether a defect is critical [11].

2.3 Design Verification

Component verification can be described as the process of assessing the conformance of key features and characteristics of an as-manufactured component to the customer's requirements. Acceptance criteria and tolerances are prescribed by designers to notify of the maximum allowable variability (being geometrical variability or otherwise). The level of inspection required for any given feature is dictated by its criticality and risk of non-conformance. Design risk is driven by performance, safety and fit whilst process risks are driven by process and inspection system capabilities. For example, due to the critical nature of aerospace components, high risk structures are subject to 100% inspection.

Several methods can be employed to detect non-conformities. The field of non-destructive testing (NDT) involves the detection and/or characterisation of damage on the surface and interior of materials without cutting the material apart. It refers to the evaluation and inspection process of components for material characterisation, and for finding defects/flaws in comparison with standards without altering the original attributes or harming the object being tested. NDT methods provide a cost-effective way to ensure production quality control [12]. Methods can be employed for both detection, where an anomaly is identified as being present in a structure, and characterisation, where features such as anomaly size and depth are defined, or for either detection or characterisation.

The inspection of composite materials poses a particular challenge; since materials are often non-homogenous and anisotropic, many traditional types of NDT do not work or are inconclusive [13]. For a defect detection method to be suitable, the response for an area of non-conformity, must be highly distinguishable from the response for an acceptable region [7]. Moreover, prior knowledge of the component configuration, including material composition and defect type to be detected, is necessary for obtaining optimal results [14].

For those methods that are acceptable, each has their own set of advantages and limitations. As a result, methods can be seen to be complementary. In order to gain all relevant information with regards to a defect both quickly and precisely, a combination of NDT methods should be considered [15], [16].

2.3.1 Ultrasonic Testing

The most commonly used method (only method leading to certification of aerospace components) is ultrasonic testing (UT), which is capable of producing a two-dimensional scan of the component [7].

UT is based on the propagation of high frequency sound waves in the order of 1-50MHz transmitted to the tested object by a transducer and couplant [7], [15], [16]. Properties of the material can be ascertained through loss of original amplitude (or energy) in the response pulse, obtained through a receiver and display unit. This pulse is dependent on how the ultrasonic wave propagates through the component, with beam incidence angle, wave velocity and material density, and how it interacts with any interfaces, grain discontinuities or defects affecting the response [12]. A portion of pulse energy is transmitted and other is reflected; the relative amount depends on the acoustic impedance of the material and attenuation [17]. The loss due to reflection is significant in composites, especially at high frequencies, due to continually changing density and velocity from anisotropic material properties [18], creating difficulties in interpreting the responses.

The advantages of UT include good resolution, flaw detection capabilities and repeatability of scans, however difficulties are encountered in set-up, skill requirements for inspection and need for reference sample to ensure accurate inspection [12]. UT has been used to evaluate the effects of fatigue and damage tolerance testing on aircraft fuselage structures [19], detect cracks in components [20] and determine the presence of disbonds in wind turbine blades [21].

There are two conventional techniques in the use of UT in composites. Where access allows, transducer and receiver units can be aligned either side of the material in order to carry out through-transmission UT. However, if this is not possible, a single transducer/receiver unit is contacted to one side to carry out pulse-echo UT. The choice of appropriate technique depends on specific application with particular consideration given to material specification and process/quality control requirements [22].

Pulse Echo Technique

The pulse-echo technique involves the detection of echoes produced when an ultrasonic pulse is introduced into the material and reflected by a discontinuity within a component [23][24]. Flaw location, depth and size can be determined; depth is determined from the time-of-flight between initial pulse and flaw echo, and size is determined from comparison of signal amplitudes from reflected sound from interface and from a reference/reflector (back wall). However, due to the nature of reflected waves, it is difficult to identify superimposed defects through component thickness [17]. Pulse-echo techniques utilise a coupling agent to counteract the effects of acoustic impedance during inspection and facilitating the transmission of ultrasonic energy. This is achieved either through full probe contact or by immersing transducer and test subject in water [17], [25].

Through Transmission Technique
Since transmitter/receiver units are placed either side of the part, ultrasonic waves only travel once through the part, resulting in less attenuation than in the pulse-echo technique, enabling a greater capability for thicker components. When discontinuities are present on the wave path, the received signal is attenuated [28]. No flaw depth information is available for discontinuities on the wave path. Similarly to pulse-echo, through-transmission techniques require a couplant – a common solution includes the use of horizontally opposed ultrasonic transducers coupled by a water jet [24].

2.3.2 Thermography

Thermographic testing (TT) technique provides a non-contact method, capable of wide area inspection and detection of subsurface defects in materials [26]. A thermal image is created by converting a emissivity radiation pattern emitted by the surface of an object into an electronic video signal [27]. Defects typically have different emissivity values to the surrounding structure [28], and therefore can be detected if an external stimulus is applied to excite the material. Heat diffusion over an irregularity in a material will differ from the surrounding area, visualised in a thermal response [29].

TT is a non-contact inspection method with fast inspection rates over a large area, which can prove advantageous for large complex components. Conversely, thermal excitation can prove difficult to distribute uniformly, and environmental effects can be difficult to control. Moreover, an empirical rule of thumb exists for detection of defects: the radius of the smallest detectable defects should be at least one to two times larger than its depth underneath the surface. TT therefore is considered to be a ‘boundary’ technique as only a limited thickness of material underneath the surface is inspectable [30].

TT has been used to detect impact damage on composite automotive panels [31] and delamination defects in composite repair patches for aircraft [32].

2.3.3 Shearography

Shearographic testing (ST) is a speckle interferometric technique used to determine surface deformation and displacement. When a component is stressed, the applied response manifests itself as a signature fringe anomaly over a region of weakness, produced by superimposing initial and deformed speckle patterns [33]–[35].

It is desirable to impose stress testing methods on the component that are similar to those experienced in service, enabling only critical flaws to be revealed. Any other cosmetic flaws that do not jeopardise structural integrity can be ignored [33]. ST can also be conducted rapidly and non-contact over large areas. Delamination defects and disbonds can be characterised well, however detection of other defect types and depth is extremely difficult [36]. Additionally, deterioration in fringe clarity can occur as result of environmental effects (e.g. external vibration) [37].

ST has been shown to be effective in the inspection of delamination in wind turbine blades [38], [39], bond failure and core crush in lifeboat hulls [40] and small deformations in the walls of composite pipes [41].

3 Knowledge Gap in NDT

The use of composites in industry has presented some unique challenges in the application of NDT; material composition and complex component geometry push the boundaries of what each technique is capable of detecting. Process verification is crucial to the safety of a component and underpins design, structural integrity and manufacturing of composites. However, composites in the aerospace industry are still designed against defect criteria and failure constraints determined decades ago [42]. A lack of experience in using composites as structural components exists in the automotive industry [43], whilst there is limited knowledge and guidance in place for utilising NDT for verification in the marine industry [44].

Through the NDT Requirements for Composites workshop series run by The British Institute of Non-Destructive Testing (BINDT), outputs recognised that the state-of-the-art for NDT methods for composites inspection is not completely clear. Therefore, a need for a high-level NDT technology map linking material type, component type and defect type to applicable NDT methods, their capabilities and limitations has been identified. A lack of sharing information relating to both NDT and materials information results in knowledge obtained being locked into a small group of experts, slowing the rate of technology development and implementation through repeated research [43], [44].

The deployment of these methods on composite components in industry can be problematic; ineffective inspection methods coupled with a lack of knowledge of how to use the method appropriately, could result in delays in production at great expense.

3.1 Composites Integrity Verification Capability Development

To support existing and future research and manufacturing programs, the National Composite Centre (NCC), Bristol UK, has identified a requirement for large scale automated NDT capabilities to be developed. The Composites Integrity Verification Cell (CIVC) [45], shown in Figure 1, has been designed to address this by providing fast, reliable and high quality automated inspections of large complex shaped composite components. Inspection systems are mounted on an automation platform, with robots with an individual repeatability of ±0.1mm to ensure improved scan resolution when compared to manual systems.

The multi-method system aims to employ UT, TT and ST methods, and provides a platform for the development and scaling of these new and existing inspection technologies. A combination of techniques can be used to inspect a complex component, optimising the results gained by using the most appropriate technique for component configuration. Similar automated inspection systems have been developed for research purposes, e.g. Mineo [46].

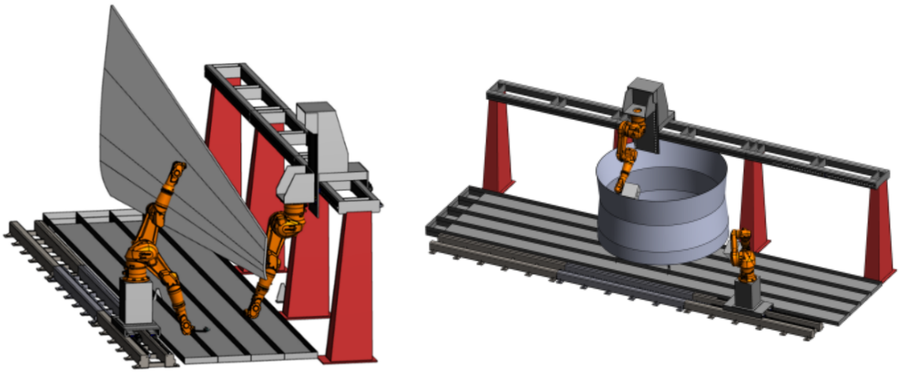

Figure 1. CAD images of application of CIVC equipment on sample components [45]

The system, installed at the NCC in October 2019, demonstrates the capability for large scale automated NDT exists, however the knowledge required to best operate the equipment for research and development programs has not yet been established.

4 Development of a High-Fidelity Knowledge Management System

4.1 Proposed Knowledge Base Development

Difficulties with NDT of composites in industry can be addressed by integrating of knowledge management practices; knowledge management systems (KMSs) enable access, coordination and processing of knowledge assets. Capturing information in a system avoids losses of relevant knowledge, improves productivity by means of information sharing, and allows informed decisional processes to occur [47], [48].

Explicit or tacit data, information and knowledge can be captured and manipulated by KMSs to form structured knowledge, with the potential to be applied to problem solving activities [49]. Codified explicit knowledge can be readily transferred and applied within an organisational environment, however research involves significant explicit knowledge, together with tacit knowledge, which is developed through experience. This tacit knowledge cannot be readily codified, and can be described as an instinctive assessment shaped by the involvement of the operator in the relevant context through social/joint interactions, for example, learning skills through apprenticeship [50]–[52]. NDT learning often falls into this type of knowledge transfer; it is very difficult to document technical "know-how" [52] in words or learn from reading, so skills are typically passed on through practical application. There is no prescribed way to produce results from an inspection, and therefore each NDT specialist operates in a way that is individual to them. Moreover, the difficulty of documenting this knowledge can negatively impact on operator willingness to share knowledge, whilst many NDT operators keep technical expertise to themselves as these skills are what make them employable [53].

4.1.1 Capability Matrix

The development of a high-fidelity knowledge base (KB) aims to address the gaps in the understanding of NDT capabilities and enable effective knowledge capture and transfer. By mapping composite material, component and defect configurations to NDT method in a database, a comprehensive understanding of the state-of-the-art capabilities and limitations of detection methods can be determined. Specimen configurations used to determine method capabilities are categorised by geometry, source materials and specimen structure (monolithic or sandwich). Inclusion, delamination/void and waviness defects are considered. Data is captured in a capability matrix, evaluated to assess performance of an inspection technique with respect to specimen configuration and assigned a red, amber or green rating to indicate effectiveness:

- Green – Method/technique is fully capable of detection and characterisation: defect location with size and depth features recorded
- Amber – Method/technique is partly capable of detection or characterisation, with limitations: defect location with either size or depth features recorded
- Red – Method/technique not capable of detection or characterisation: defect location and features cannot be recorded

Best practice guidelines will be developed from this data to baseline inspection processes.

4.1.2 Anticipated Benefits

The primary function of the knowledge base is to further NDT knowledge by testing and capturing the current state of methods and techniques, informing future inspection processes. However, this organised information can be fed back from NDT into design and manufacturing teams, resulting in augmentation of decisions and enabling design for NDT methods to be incorporated early in the product design process. By understanding the capabilities and limitations of a detection method, validation data can provide improved assurance and confidence in design; component design can be optimised to reduce safety factors, knowing the controls to detect anomalies (if any) are effective, improving the competitive advantage of an organisation.

Since the KB aims to comprise of detailed information on the current state of NDT methods, it will be possible to identify where an information deficit exists. This deficiency can then be used to determine where research efforts into improving NDT capabilities should be centred, based on future inspection requirements.

4.2 Deployment of Knowledge Base

The KB will aim to provide validated applicability data can be used to support method selection through knowledge-based decision making on the NCC's CIVC. With a choice of UT, TT or ST methods, the most effective detection method, and specific technique, can be chosen depending on component or feature (small area of a larger component) configuration to produce overall optimised results. Without deploying the KB in this decision process, CIVC may risk failure of being used effectively on complex parts.

Inspection requirements should be considered when assessing the component against the KB, with attention to necessary outputs; a less time-consuming method could be used over an expensive method if requirements demand only detection, not characterisation.

4.3 Alternative Knowledge Management Systems

The idea of introducing a KMS for NDT is not a novel concept; Summerscales [54] presented a preliminary assessment of the capabilities of various NDT methods for the detection of several defects, indicating if an established technology has applicability in the detection of the defect. This work formed the basis of an NDT Selection Tool, developed by ESR Technology, QinetiQ and NetComposites with funding from the UK Government. Launched in 2007, the tool intended to provide advice for industrial users for information on NDT of composite materials [55]. HOIS Joint Industry Project group aims to advance NDT in the oil and gas industry by developing technologies and understanding of NDT methods through an interactive knowledge base (IKB) [56], [57].

However, neither of these systems are available for public use; NetComposites NDT Selection Tool is not currently accessible and HOIS IKB access is restricted to HOIS members only. The proposed KB presented in this paper is necessary to fulfil the requirements of the ~£1.3m CIVC system capability, and once effectiveness of the decision tool has been validated though deployment on CIVC, the KB will be disseminated to the wider NDT community and made accessible through the NCC. For the KB to be an evolving knowledge management system within the NDT community, it must be easily understandable, effective when used and compatible with existing working systems. To demonstrate worth, the community must employ it on projects and continuously expand the repository when new knowledge is acquired.

5 Conclusions

Development of a KMS mapping composite material, component and defect configurations to NDT method is necessary to capture current understanding of detection method capabilities and limitations, addressing the gap in NDT knowledge identified by industry. UT, TT and ST method performance is evaluated in a capability matrix, assessing performance against specimen configuration, and assigned a red-amber-green rating indicating efficacy of a process. Baselining these processes using best practice guidelines will ensure knowledge capture and transfer can be achieved through standardisation of inspection.

By understanding what NDT methods can realistically verify, design and manufacturing teams can make informed decisions for product optimisation at early stages of the design process with improved confidence, closing the Design for X loop. Moreover, capturing the current state will highlight where the deficiencies in NDT knowledge exist. Implementing the KB as a decision tool in industry and on the NCC's CIVC, in conjunction with requirements, will enable method selection for optimised results.

Forthcoming steps for KB development involve continued testing of specimens for the population of the NDT capability matrix. Manufacture of specimens that are representative of components used in industry are required for testing to ensure the KB remains relevant for industrial purposes.

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